

Compact Nuclei in Moderately Redshifted Galaxies

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ABSTRACT

The Hubble Space Telescope WFPC2 is being used to obtain high-resolution images ($\leq 0.15''$ FWHM) in the V (F606W) and I (F814W) bands for several thousand distant galaxies as part of the Medium Deep Survey (MDS). An important scientific aim of the MDS is to identify possible AGN candidates from these images in order to measure the faint end of the AGN luminosity function as well as to study the host galaxies of AGNs and nuclear starburst systems. We are able to identify candidate objects based on morphology. Candidates are selected by fitting bulge+disk models and bulge+disk+point source nuclei models to HST imaged galaxies and determining the best model fit to the galaxy light profile.

We present results from a sample of MDS galaxies with $I \lesssim 21.5$ mag that have been searched for AGN/starburst nuclei in this manner. We identify 84 candidates with unresolved nuclei in a sample of 825 galaxies. For the expected range of galaxy redshifts, all normal bulges are resolved. Most of the candidates are found in galaxies displaying exponential disks with some containing an additional bulge component. 5% of the hosts are dominated by an $r^{-1/4}$ bulge. The V-I color distribution of the nuclei is consistent with a dominant population of Seyfert-type nuclei combined with an additional population of starbursts. Our results suggest that $\sim 10\% \pm 1\%$ of field galaxies at $z \lesssim 0.6$ may contain AGN/starburst nuclei that are 1 to 5 magnitudes fainter than the host galaxies.

Subject headings: galaxies:active-nuclei-starburst

1. Introduction

Accurate knowledge of the luminosity function (LF) of active galactic nuclei over a wide range of absolute magnitudes is necessary to understand the nature and evolution of these objects. The faint end of the AGN LF ($M_B \geq -23$) has been determined using Seyfert galaxy nuclei which are considered to be the intrinsically fainter counterparts of more distant, brighter AGNs (Cheng et al. 1985). The behavior of the LF as a function of redshift can be used to derive the manner in which AGNs evolve. Understanding how the faint end of the AGN LF evolves is necessary to determine the frequency and total space density of these objects at earlier epochs. One interesting question this information addresses is the contribution of Low Luminosity AGNs (LLAGNs) to the soft X-ray background (2-10 keV) (Elvis et al. 1984) (Koratkar et al. 1995).

The evolution of the faint end of the LF is difficult to measure. Even at modest redshifts, low-luminosity AGNs become virtually impossible to observe from the ground. In ground-based images the unresolved nuclei cannot be distinguished from central regions of enhanced star formation or finite central density cusps of spheroidal components. The Hubble Space Telescope eliminates this problem with its unique high resolution imaging capabilities.

The Medium Deep Survey (MDS) (Griffiths et al. 1994) yields 2-4 parallel WFPC2 exposures per week, each containing ~ 300 galaxies down to $V \sim 23.5$ mag. This survey provides an ideal sample of distant field galaxies for which morphology and light-profiles can be studied for the first time at sub-kpc resolution. Typical galaxy redshifts are within $z \leq 0.6$ (Mutz et al. 1994). The set of Cycle 4 and 5 images consists of ~ 100 fields with both V and I exposures, in which weak stellar nuclei can be distinguished in galaxies with integrated magnitudes down to $V \sim 22$ mag. In this analysis, we search all galaxies in 59 MDS fields to a limiting magnitude of $I \lesssim 21.5$ for unresolved nuclei which may indicate a

possible AGN or starburst.

2. HST Observations

The HST images used in this study were taken in “parallel mode” several arcminutes from the primary target in random locations spanning the entire range of RA and with $-16:16 \leq \text{Dec} \leq 85:20$. Avoiding low galactic latitudes, we chose fields with $|b| \geq 20$. The details of the MDS observing strategy and data reductions can be found in Griffiths et al. (1994). On average, there are ~ 14 galaxies with $I \leq 21.5$ in each WFPC2 field. We present here 53 MDS fields having at least 2 exposures in both V and I and with total exposure times between 2000 and 23,100 seconds. We also include 6 fields with I images alone having comparable exposure times. Our limiting magnitude of $I \leq 21.5$ is at least 3 magnitudes above that for detecting point sources in any of our selected MDS fields. This limit allows for uniform galaxy detectability across the range of exposure times.

3. Galaxy Modeling

We use a modeling approach based on maximum likelihood estimates to extract quantitative morphological and structural parameters of the faint galaxy images in the MDS. Details of these fitting techniques are described in Ratnatunga et al. (1994) and Ratnatunga et al. (1996). We perform a simultaneous 2-dimensional fit of all major components of the light profile: exponential disk, $r^{-1/4}$ bulge, and Gaussian point source. The unconvolved half light radius for a point source is kept fixed at $0.018''$. Once this model is convolved with the WFPC2 PSF, the gaussian source has a FWHM of $\sim 0.15''$ which agrees well with fits to stars in the image. The fitting procedure allows for a choice of models to be fit to each galaxy: a 7-parameter pure bulge or disk model, an 10-parameter bulge+disk

model, a 10-parameter disk+point source model, and a 13-parameter disk+bulge+point source model. Chi-square minimization techniques are used to determine the model parameters of the best fit to the galaxy light profile. These parameters include total galaxy magnitude, sky magnitude, X and Y position, half-light radius and position angle of the primary component, disk and bulge axis ratios, bulge-to-total galaxy light ratio, bulge-to-disk half light radius ratio, point source-to-total galaxy light ratio, and position of the point source with respect to the disk and/or bulge center. The point source position was constrained to be $\lesssim 0.2''$ from the disk or bulge central position to avoid fitting non-nuclear knots and irregularities seen in many galaxies with active star formation. The best model fit is determined by comparing the computed likelihood estimation values. In addition each galaxy was individually examined to verify the goodness of fit for each model and note highly irregular galaxies which were not well fit by any model.

It is important to find not only the best fit, but a unique fit to each galaxy. In some cases a fit with the point source included was not significantly better than the simple bulge+disk model alone. To determine the significance of the difference in computed likelihood estimates of each fit, we performed the same fitting procedures on simulated galaxies with a range in magnitude, bulge-to-total light ratio, and half-light radius. These galaxies did not contain point source nuclei and consisted of pure bulge+disk components. We also conducted fitting tests using real galaxy images from our sample with simulated point sources superimposed in the nucleus. Based on the results of the fits to these simulated galaxies, we were able to determine a significance level for the detection of a point source component in our sample galaxies. This significance level was used to filter spurious detections of point source components which were insignificant as compared to the simple bulge+disk model fits for our galaxies.

An unresolved source at $z=0.1$, assuming WFPC2 resolution of $0.15''$, corresponds to

an actual size of <370 pc, using $H_0=75$ km/s/Mpc and $q_0=0.5$. At $z=0.6$, this corresponds to a size of <1140 pc. The emitting regions of Seyfert 1 or Seyfert 2 nuclei as well as those of smaller starburst regions, would lie well within these boundaries. These sizes are smaller than the typical bulge sizes of late type spirals making it unlikely that the unresolved regions in the majority of our galaxies are due to a simple bulge component. Our most distant late-type spirals, however, could contain bulge components that are near the unresolved region size and may therefore be included in our sample. The contribution of unresolved bulges should be small since the current galaxy redshift distribution for MDS galaxies peaks near $z\sim 0.3$ and steadily decreases to $z\sim 0.6$.

4. Number Counts

We find 84 galaxies requiring a nuclear, unresolved point source component in the galaxy model. This sample consists of 21 sources detected in I frames only, 8 in V frames only, and 55 in both I and V representing $10.2\pm 1.1\%$ of the total 825 galaxies in our magnitude-limited survey. Almost all of the host galaxies for these sources contained significant exponential disks, consistent with the morphology of Seyfert galaxies or nuclear starburst galaxies. 57% of the host galaxies were adequately modeled with an exponential disk alone while 38% required an additional bulge component in the fit. 5% required a dominant bulge component where the bulge contributes $\geq 80\%$ of the total galaxy light. We note that our search is not sensitive to pure stellar-like quasars which would probably be identified as stars in our initial galaxy search. Apparent magnitudes for the nuclei range from $20\leq I\leq 26$ and $21\leq V\leq 27$. If we assume our galaxies to be at $0.1\leq z\leq 0.6$, a probable absolute magnitude range for our nuclei is $-21\lesssim M_V\lesssim -14$. The nuclei make up between 1% and 50% of the total galaxy light with all but 8 having nuclei comprising less than 20%. Detections to the 1% level were obtained in all fields across the range of exposure times

such that there is no apparent incompleteness due to short exposure time fields. Figure 1 shows examples of galaxies in our sample requiring a nuclear point source component in the galaxy fit.

Of the remaining 741 galaxies in our magnitude-limited sample not requiring an additional point source component, 463 required a bulge and disk fit in both V and I to accurately model the galaxy light. 160 required a pure disk model and 100 required a pure or dominating ($\geq 80\%$) bulge model. 18 were not well fit by any model due to irregularity.

We estimate our incompleteness by comparing the measured nuclear magnitude to that of the total integrated galaxy magnitude. We find that the faintest point source component which can be detected comprises $\sim 1\%$ of the total galaxy light. At a galaxy limiting magnitude of $I \leq 21.5$, we are above the photon noise limited regime in detecting point source components. Our detection limit is imposed by noise elements in the images such as flat fielding effects, cosmic ray removal, etc. Some galaxies contained additional structural elements in the nucleus such as rings and bars, but they were found to be relatively insignificant noise sources. Based on our detection limits and the distribution of galaxy magnitudes in our sample, we are $\sim 80\%$ complete in searching for nuclei down to 5 mags fainter than the total galaxy apparent magnitude for all galaxies in both V and I. For galaxies at the bright end of our distribution ($19.5 \lesssim I \lesssim 18.0$) the detection limit for a point source component increases from 1% to $\sim 3\%$ of the total galaxy light. Small number statistics at the bright end of our distribution make it difficult to determine the completeness in searching for faint nuclei in these galaxies. We estimate that we are $\sim 93\%$ complete in searching for nuclei down to 3.8 mags fainter than the galaxy apparent magnitude. We have not incorporated this incompleteness into our number counts of unresolved nuclei.

5. Nuclei and Host Galaxy Colors

Figure 2 shows the normalized distribution of V-I colors for the 55 nuclei in our sample where accurate V *and* I magnitudes were measurable. The typical error in V-I color is $\pm\sim 0.2$ mag. The mean V-I color of known Seyfert 1s/QSOs from Elvis et al. (1994) at $z\leq 0.5$, typical of the galaxy redshifts in MDS fields, is indicated at 0.85. These QSOs/Seyfert 1s are dominated in ground-based images by their active nuclei and should be valid for comparison with our nuclear colors. We also indicate the mean V-I color of Seyfert 2 nuclei based on data from Kalinkov et al. (1993). They measure a mean B-V color for Seyfert 2 nuclei of 0.71. Assuming a power-law spectral energy distribution, we transform to V-I and estimate a color of 1.35.

Our sample reveals a large range in colors with a dominant population at $V-I\approx 1.25$. This distribution might be explained by the presence of more than one object type in our sample. A broad, shallow distribution may result from starbursts seen at various stages of evolution and/or broadened by reddening due to dust. Colors for starburst nuclei based on spectra from Bica et al (1990) range from $V-I = 0.2$ during the young HII region phase to $V-I = 1.3$ or more for intermediate age clusters at ≥ 7 Gyr. The blue tail of our distribution may consist of starburst nuclei since the colors are bluer than those expected for QSOs/Sy1s and are probably due to the presence of young stars. Our peak falls close to the predicted Sy2 nuclear color with a blue side asymmetry biased toward Sy1 colors suggesting that the dominant population may be AGN-related.

Figure 3 shows the integrated host galaxy color versus the nuclear color in V-I for the 55 sources detected in both the V and I images. The host galaxies have colors in the range $0.5\lesssim V-I\lesssim 2$ with roughly half having bluer nuclei and half containing redder nuclei. There is not a 1-to-1 relation between the galaxy color and nuclear color, indicating that the point source is not simply a fitting residual in the galaxy. We did not require that the nuclei

necessarily differ in color from the underlying host galaxy for sample selection. However, an elliptical or bulge-dominated galaxy could be sufficiently cuspy in the nucleus such that an additional point source component improves the model fit. To avoid cuspy bulges in our selected sample, we removed 8 galaxies which were well fit with an elliptical-type galaxy plus a point source of the same color as the galaxy.

6. Summary and Discussion

In summary, we find that in a magnitude-limited survey ($I \leq 21.5$) of 825 galaxies estimated to be at moderate redshifts, 84 contain unresolved nuclear point sources. This represents $10.2 \pm 1.1\%$ of all galaxies in our sample. Almost all of the host galaxies of these nuclei are spirals with some displaying significant bulge components and a small fraction residing in elliptical hosts.

V-I colors for the nuclei cover a large range and might be attributed to the presence of different object types in our sample. The distribution is consistent with a population of Seyfert-like galaxies combined with a population of starburst nuclei at various stages in their evolution or which have been reddened to various degrees by the presence of dust.

Since the V-I colors of starburst nuclei and AGN nuclei are likely to overlap, we cannot explicitly separate the two populations in our sample. Due to the peaked nature of our color distribution, we might assume that one or the other dominates. For the purposes of comparison, let us assume that the dominant population represented in our nuclei sample is AGN-like. If so, how do our counts compare with previous studies of the incidence of these objects? Recent results from the Canada-France Redshift Survey (Tresse et al. 1996) find that between 8% and 17% of the galaxies at $z \leq 0.3$ are narrow-line AGNs based on line ratio diagnostics. Locally, Huchra and Burg (1992) find the fraction of AGNs in the CfA redshift

survey of 2400 galaxies to be $\sim 2\%$ based on spectroscopic identification. Differences in identification of AGN based on spectroscopy and morphology, however, allow intrinsically fainter AGNs to be detected in our survey. Although our galaxy absolute magnitudes may cover the same range, our nuclear absolute magnitudes are certainly fainter than those observed in the CfA or CFRS studies. Granato et al. (1993) show that many Seyfert 1s in the CfA survey have nuclei contributing between 30% and 90% of the total galaxy light whereas our nuclei typically contribute less than 20%. A fainter absolute magnitude limit combined with the apparent steepness of the AGN LF at low redshifts (Cheng et al. 1985) could account for an apparent increase in number density from 2% locally to $\sim 10\%$ at moderate redshifts.

We are currently obtaining ground-based spectra of galaxies containing AGN/starburst nuclear candidates for redshift information as well as possible spectral identifications. Also, recent MDS fields include B-band exposures in addition to V and I which will provide increased color information for the identified nuclei. We will be expanding this study to include more MDS fields to increase our sample of unresolved nuclei. With the additional spectroscopic and color information, the question of LF evolution of fainter AGNs can be addressed directly.

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FIGURE CAPTIONS

Figure 1 - V filter image of MDS galaxies containing unresolved nuclear components.

Figure 2 - (V-I) color histogram for unresolved nuclear sources. The mean (V-I) color of 49 Seyfert 1s/QSOs from Elvis et al. (1994) is indicated by an arrow as well as the mean color for Seyfert 2s based on data from Kalinkov et al. (1993).

Figure 3 - (V-I) color of the integrated galaxy versus the (V-I) color of the unresolved nucleus for the 55 sources detected in both the V and I images.





